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ARMY AIRCRAFT PROTECTIVE STRUCTURES DESIGNS

Report 3

RESPONSE OF SELECTED MATERIALS TO HIGH-SPEED FRAGMENT IMPACT

by

J. W. Brown, W. G. Dykes

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ABSTRACT

In order to design effective fragment protection schemes that will allow optimum use of time, personnel, and materials, it is necessary to understand the behavior of various materials under fragment impact. Therefore, a study has been conducted using textiles, wood, and earth materials to gain an understanding of the basic physical laws governing their response to fragment impact.

Mathematical analyses of the physical characteristics of the various materials as well as experiments in which fragment simulating projectiles were used have yielded insight into the basic mechanics of fragment defeat. Materials were tested by impacting them with projectiles weighing between 17 and 300 grains at velocities ranging from 500 to 5,000 ft/sec. Data from these tests are presented to illustrate the relations between mass, velocity, and penetration depths of the projectiles into ballistic nylon, wood, sand, and clay.

Three different failure modes that are dependent on the impact velocity of the projectile were identified for ballistic nylon. Test results showed that as the projectile impact velocity increased, a critical velocity was reached at which the nylon sheared immediately upon impact, offering little resistance to penetration. Test results also indicated that the relation between thickness and effectiveness of nylon was not linear, i.e., doubling the thickness of the nylon did not double its resistance to penetration. The information gained in the study of nylon was extrapolated to other textiles through consideration of the physical properties of the textiles,thus eliminating the need to test each textile by actual fragment impact.

The effectiveness of plywood as a fragment defeating material is shown in curves that describe depth of penetration or residual velocity for fragments that penetrate. The wood was quite linear in its ability to defeat fragments, as doubling its thickness doubled the impact velocity that a fragment must have to penetrate.

Depths of penetration relative to striking velocity are presented for sand and clay. The sand tests revealed some interesting results. For

example, in sand, the projectile penetration depth increased with striking velocity only to a velocity of approximately 3,500 ft/sec. At this point, increasing velocities resulted in proportionately decreasing penetration depths. The clay tests indicated that as fragment striking velocity increased, penetration depth increased in a decreasing fashion, with the additional energy evidently being dissipated in the creation of a conical cavity the volume of which increased with striking velocity.

Based on the results obtained in this study, it is recommended that tests and studies be continued on new materials and on the interesting characteristics of sand.

PREFACE

The study reported herein was conducted by the Nuclear Weapons Effects Division (NWED) of the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers, as part of the Army Aircraft Protective Structures Program, Project 4A662708A859, of the Military Engineering Design and Expedient Construction Criteria Project.

The study was conducted during the period February through August 1969 under the general supervision of Mr. G. L. Arbuthnot, Jr., Chief of the NWED, and Mr. W. J. Flathau, Chief of the Protective Structures Branch, and under the direct supervision of Mr. J. T. Ballard, Chief of the Operations Group. This report was prepared by Mr. J. W. Brown of the Analytical Research Group, NWED, and Mr. W. G. Dykes of the Engineering Branch, Construction Services Division, WES.

Directors of the WES during the conduct of this investigation and the preparation and publication of this report were COL Levi A. Brown, CE, and COL Ernest D. Peixotto, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows.

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
square feet	0.092903	square meters
square yards	0.836127	square meters
ounces	28.3495	grams
grains	0.0648	grams
pounds	0.45359237	kilograms
ounces per square foot	0.30515	kilograms per square meter
ounces per square yard	0.03391	kilograms per square meter
cubic feet	0.0283168	cubic meters
feet per second	0.3048	meters per second

INTRODUCTION

BACKGROUND

The work described herein was conducted as part of the Army Aircraft Protective Structures Program; this is one of a series of reports dealing with this subject. During the early phases of the Aircraft Structures Program work, it became evident to researchers that information dealing with the mechanics of fragments and the ability of various materials to defeat fragments was not readily available. Thus, a study of fragment mechanics and the effects of fragments on various materials was conducted to provide designers with facts to be used in solving the protection problem.

OBJECTIVES

Ultimate objectives of the fragment mechanics study were to obtain information on the ability of various materials to stop the penetration of fragments from indirect-fire weapons and to define optimum orientation of the materials whether used singularly or in combination with each other. Before these objectives could be realized, several intermediate goals had to be reached. A logical method of simulating a fragment by some standard projectile had to be selected, and a facility for propelling the projectile under closely controlled conditions had to be constructed. Researchers had to choose from among many possible protective materials those few that best met Army needs regarding availability, cost, weight, ease of construction, and effectiveness. A test program had to be conducted, and the accumulated data analyzed in order to categorize the best of the available data. Materials showing promise in the laboratory were selected for full-scale field testing. Results of the field tests are included in Report 1 of this report series.[1] This report describes the handling of each of the intermediate goals described above and lists the conclusions drawn from each phase of the work.

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[1] G. L. Carre and W. L. Huff; "Army Aircraft Protective Structures Designs; Helicopter Revetment Systems Using Field-Available Materials for Protection Against Weapon Fragmentation"; Technical Report N-69-8, Report 1, November 1969; U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi; Unclassified.

TESTS AND RESULTS

DESCRIPTION OF PHYSICAL FACILITIES

The fragment simulation facility consists of an underground firing range and an outside support building (Figure 1). The underground structure is an 8-gage, galvanized steel, multiplate-pipe arch with a span of 12 feet 8 inches[2] and a rise of 8 feet 1 inch and is 32 feet long. The end walls are made of prefabricated 1/4-inch-thick steel plate and are bolted to the arch section. One of the end walls has an 8-gage, galvanized steel, multiplate cattle-pass entrance. When firing is in progress, access to the test chamber is prevented by a 1/2-inch-thick steel inner door and a 1/4-inch-thick steel outer door. The outside support building houses the firing switch, a recorder for recording time of flight, and a cartridge preparation area that includes the equipment necessary to handload the fragment simulating cartridges.

FIRING DEVICES AND PROJECTILES

First Firing Device. Three firing devices were used to propel a variety of fragments. The first device was a Remington Model 660, .222-caliber sporting rifle. This rifle shoots the 17-grain fragment simulating projectile (FSP) developed by the Ballistic Research Laboratory at the Aberdeen Proving Ground, Maryland. Velocities in excess of 4,000 ft/sec are possible with this projectile. The projectile is spin stabilized, point hardened, and ballistically quite efficient and, therefore, has been used infrequently in the test program as it is believed to represent projectiles of direct-fire weapons (rifles) rather than those of indirect-fire, fragment-producing weapons.

Second Firing Device. The second firing device was a Remington Model 660, .350-Magnum-caliber rifle. The FSP used extensively with this device was a 21-grain steel cube that measured 0.218 inch on each side. The

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[2] A table of factors for converting British units of measurement to metric units is presented on page 8.

21-grain weight was chosen after careful study of the fragments generated by various weapons of interest. Likewise, the cubic geometry was chosen as the most representative shape of the fragments of interest. Acrylic-plastic sabots, sufficiently heavy to withstand the forces of acceleration yet light enough to break up after leaving the muzzle, were developed to carry the FSP down the bore. The sabots used in firing were right-circular cylindrical cups with a 0.358-inch outside diameter, a 0.308-inch inside diameter, and a 0.100-, 0.200-, or 0.300-inch base thickness, depending on the strength required. The 21-grain FSP was placed in a sabot, which was then handloaded into a primed and charged cartridge case. Commercially available equipment was used for loading the cartridge case. The .350-Magnum cartridge was used to propel the 21-grain cube at velocities exceeding 5,000 ft/sec. Pressure readings indicated that, with a specially designed sabot, muzzle velocities of 6,000 ft/sec were possibly within the capabilities of the system.

This firing device and sabot combination also has the capability of firing actual fragments collected from fired mortars and rockets. Actual fragments of approximately 15 grains can be fired in the sabot at velocities ranging from 1,000 to 5,000 ft/sec.

<u>Third Firing Device</u>. The third firing device had the bore dimensions of a standard 12-gage shotgun, with a heavy barrel especially fitted with an additional chamber. This chamber held a .222-caliber rifle cartridge without projectile, which was used as a booster to ignite the main charge in the 12-gage bore. This two-stage firing mechanism allowed utilization of both the inherent high strength of a brass cartridge case and the increased projectile delivering capability of the larger bore. A plastic sabot was used to carry a 303-grain cylindrical steel projectile in the bore through a velocity range of 500 to 2,700 ft/sec. It came into use late in the program as researchers attempted to simulate the very large fragments produced by some weapons, most noticeably the U. S. 4.2-inch mortar and the Soviet 122-mm rocket. Continued testing with this projectile is in progress, and only preliminary results are presented herein.

VELOCITY MEASUREMENTS

Velocity measurements were made with two Oehler Research Model 20 chronographs. One recorded the projectile velocity 5 feet in front of the test sample (V_1), and the second recorded the projectile velocity 5 feet behind the test sample (V_2). An empirical velocity decay equation (Figure 2) was developed by firing the 21-grain FSP through the velocity screens with the sample removed. This indicated the loss of velocity of the 21-grain FSP as it traveled through air. This equation was then used to correct velocity measurements V_1 and V_2 to give actual striking velocity (V_s) and exit velocity (V_e) at the sample surface during tests.

ANALYSIS OF MATERIAL RESPONSE TO FRAGMENTS

Response Patterns of Textile Filaments. Considerable theoretical work has been done regarding the behavior of textile filaments under high-speed tensile impact.[3,4,5] Some of the results of this work are useful in explaining the method by which ballistic nylon defeats fragments and in determining the best amount and orientation of the material.

When a high-speed fragment strikes a nylon filament, the filament responds by moving in the direction of the fragment motion if the fragment velocity is not too high. This motion creates a transverse wave in the filament, and, simultaneously, two tensile strain waves propagate along the filament in opposite directions from the point of fragment impact. The configuration of impacted filament prior to breaking is shown in Figure 3.

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[3] C. R. Maheux and others; "Dynamics of Body-Armor Materials Under High-Speed Impact; Transient Deformation, Rate of Deformation and Energy Absorption in Single and Multilayer Armor Panels"; Report No. 2141, October 1957; U. S. Army Chemical Warfare Laboratories, Army Chemical Center, Maryland; Unclassified.

[4] J. C. Smith, F. L. McCrackin, and H. F. Schiefer; "The Impact-Absorbing Capacity of Textile Yarns"; Bulletin No. 220, February 1957, Pages 52-56; American Society for Testing Materials, Philadelphia, Pennsylvania; Unclassified.

[5] C. Smith, C. A. Fenstermaker, and P. J. Shouse; "Behavior of Filamentous Materials Subjected to High-Speed Tensile Impact"; Special Technical Publication No. 336, 1963, Pages 47-69; American Society for Testing and Materials, Philadelphia, Pennsylvania; Unclassified.

In Figure 3, Point I is the impact point of the fragment, and Point A shows the position of the head of the transverse wave. Point C indicates the head of the tensile wave, and Point B shows the end of this wave. Point D indicates material that is neither strained nor moving with the transverse wave.

The velocity of the transverse wave front, U , at Point A is related to the tension, strain, and density of the filament by this equation:

$$U = \sqrt{\frac{T}{M(1 + \epsilon)}}$$

Where: T = tension in the filament

M = linear density of the unstrained filament

ϵ = strain of the filament

Here U is expressed in Lagrangian rather than fixed coordinates. It is evident from the equation that whenever the local strain at the impact point is great enough to produce rupture of the filament, the tension drops to zero, and the transverse wave no longer propagates. Thus, the amount of filament moving in the transverse wave and the amount of energy absorbed to produce the transverse wave are highly dependent on the time at which rupture strain is reached.

In addition to transferring energy to the filament to produce the transverse wave, the fragment also transfers energy to produce the tensile strain wave. Because of the interdependence of the transverse and tensile waves, the rupture of the filament also causes an end to the propagation of the strain wave. Thus, the rate of strain is very important in determining how much energy is transferred from the projectile to the filament before the filament breaks, and this rate of strain is directly proportional to the velocity of the fragment.

One other important fact should be considered in describing the behavior of the filament during transverse impact. There is a velocity limit on the propagation of the transverse wave. This velocity limit has been termed the critical velocity, and when a filament is struck by a projectile at the critical velocity, the local strain becomes sufficient to produce rupture before the transverse or tensile waves are formed. The projectile

shears through the filament immediately upon impact, and the only energy lost by the projectile is that required for shearing the filament.

These ideas allow the identification of three distinct response patterns of a textile to a transverse impact. These response patterns are designated as tensile, transitional, and shear responses (Figure 4). The characteristics of each response pattern are presented below.

1. Tensile response occurs at low impact velocities (≤1,200 ft/sec). The local strain around the projectile impact point does not reach the level required for breaking the filament until a considerable amount of the filament has responded in tension and transverse motion, resulting in a maximum transfer of energy from fragment to filament. Some textiles, notably nylon, can absorb relatively large amounts of energy at this low strain rate. The total amount of energy absorbed prior to rupture of the filament depends on the mass of the filament and its specific breaking energy. The specific breaking energy is proportional to the area under a tension-strain curve from no strain to rupture strain for the material. These are physical parameters that can be evaluated for various textiles and used in comparing their relative energy absorption characteristics.

2. Transitional response occurs when a fragment strikes nylon at an intermediate velocity level (≈1,200 to 2,200 ft/sec). At this level, the transverse wave can form and begin to propagate, but only to a small extent. Little material is put into tension, and an even smaller amount of the filament is set into motion. The rate of strain is much higher than the rate of propagation of the transverse wave, and breaking strain is reached sooner, resulting in a decrease in the energy transfer from fragment to filament. However, the amount of energy transferred is still significant.

3. Shear response occurs when the impact velocity is so high (≈2,200 ft/sec) that the filament will not begin to transmit the transverse wave before the local strain is sufficient to produce breaking. As stated earlier, this velocity is called the critical velocity, and at or above the critical velocity, the filament shears immediately upon impact. No transverse or tensile waves are formed, and the energy transferred during this type response is minimal. In fact, the energy transfer at this velocity is so low that a textile should not be considered for use as a fragment

defeating material if fragment velocities higher than the critical velocity are anticipated.

From the information presented above, it can be seen that for a textile material to be effective in defeating fragments it should possess the following characteristics: (a) it should withstand a high critical velocity; (b) it should stretch for a high percentage of its length before breaking; and (c) it should require a high level of energy to stretch the fiber of which it is made. Table 1 (taken from reference cited in footnote 4 on page 12) shows that nylon possesses a better combination of these characteristics than do other synthetic fabrics.

Empirical Data on Response of Ballistic Nylon. Many tests were conducted to evaluate the fragment defeating capability of ballistic nylon. This material is referred to in Army supply channels as "Federal Stock Number 8305-261-85 lb, cloth, ballistic, nylon, basket weave, 13.5 oz minimum, 15 oz maximum wt/sq yd." A 12-ply blanket with grommets and exterior weatherproof cover weighs approximately 21 oz/sq ft, and the procurement cost is approximately $3.60 per sq ft.

Various sample thicknesses and orientations of ballistic nylon were tested in the fragment simulation facility. Projectiles were fired at the samples from a distance of 11 feet, and velocities of the projectiles were chronographed in front of and behind the samples. This arrangement allowed a determination of both the velocity needed to penetrate the sample and the velocity loss that the projectile sustained when the striking velocity was high enough to cause penetration.

Results of some of the tests are presented in Figures 5 through 7. The curves in the figures are based on the velocity change of a 21-grain cube impacting loose-hanging nylon at right angles. From Figures 5 and 6, it can be seen that for 8-, 12-, 16-, and 32-ply nylon blankets the loss in projectile velocity (and hence loss of momentum) was essentially constant regardless of the striking velocity. Figure 7 shows an increase in energy absorption by the nylon with an increase in striking velocity. However, when the striking velocity was high enough to keep the projectile moving in the material at more than 2,200 ft/sec, the effectiveness of the nylon declined sharply.

In addition to the tests discussed above, tests were also conducted with fragments striking the material at various impact angles, with the material wet, with the material under slight tension, and with the plies of the material separated to produce air gaps. No curves are given for these tests, as they showed no important changes in the behavior of the nylon. The results are summarized as follows:

1. The loss in velocity that the projectile sustains when penetrating a ballistic nylon blanket is minimum if the projectile maintains a velocity greater than 2,200 ft/sec while passing through the blanket.

2. Doubling the thickness of a nylon blanket will not double its effectiveness in stopping fragments.

3. There is no significant change in the effectiveness of the nylon if it is angled up to 45 degrees relative to the path of the projectile.

4. There is no significant change in the effectiveness of the nylon whether it is hanging loose or is under slight tension.

5. Wet nylon is as effective as dry nylon.

6. Air gaps between individual or groups of nylon layers do not increase the effectiveness of the blanket.

7. At velocities greater than 2,000 ft/sec, a projectile will lose as much velocity in passing through 10 feet of air as in passing through four layers of standard nylon.

8. A projectile can be stopped by 32 plies of nylon if its striking velocity is nearly critical. Adding layers beyond 32 plies yields diminishing returns, as test results showed that the fragment that could penetrate 32 plies could generally penetrate 64 plies as well. This indicates that the nylon blanket is more effective in the low-velocity regions (below 2,200 ft/sec), and adding plies does not increase effectiveness enough to justify the additional cost and weight.

Response of Plywood. Both the 21-grain cube and the 303-grain cylinder were used in studying the response of 3/4-inch fir plywood to fragment impact. Results of the tests are plotted in Figures 8 and 9. Unlike ballistic nylon, the plywood seems to respond independently of the velocity of the projectile. The velocity loss that the projectile sustains when passing through the plywood is nearly the same over a very broad range

of velocities. Also, the effectiveness of the plywood is nearly linear with thickness.

Velocity loss is essentially constant in plywood regardless of impact velocity, whereas ballistic nylon loses its effectiveness with increasing impact velocity. Therefore, if plywood and nylon are used in combination, the plywood should be placed in front of the nylon, which will enable the fragment velocity to be reduced by the wood prior to entering the nylon to a velocity at which the nylon becomes more effective (see Figure 10).

Response of Sand and Clay. Tests were run on both dry and saturated sand in order to gain some idea of its effectiveness under general outdoor conditions. These sand samples were contained in 1-cu-ft boxes made from 1/2-inch plywood. The sand, either wet or dry, proved highly resistant to penetration by the 21-grain cube. The curves in Figure 11 illustrate the effectiveness of the sand in stopping fragments and also show the tendency of the projectile to reach a maximum depth of penetration at velocities of approximately 3,000 and 3,500 ft/sec in dry and wet sand, respectively. Velocities greater than 3,500 ft/sec do not yield increased penetration.

The shots into moist clay (20 to 25 percent moisture) showed other interesting tendencies. The impact of a projectile into a clay sample caused a conical void in the clay with the projectile stopping in the vertex (see Figures 12 through 16). Change in the depth of the cone was not linear with a change in striking velocity. However, the volume of the cone increased with increased striking velocity. Evidently, energy of a projectile is expended both in penetration and creation of a cavity, and the latter becomes more important as velocity increases (see Figures 12 through 16).

Although the basic reasons for the interesting response of soil to fragment impact are fit subjects for excellent theoretical analyses, the practical fact learned from the tests conducted during this investigation is that in all the shots conducted, none of the fragment simulating projectiles completely penetrated 1 foot of earth material. When cost, effectiveness, and availability are considered, earth material remains an excellent choice for protective structure construction.

SUMMARY AND RECOMMENDATIONS

The fragment threat from a wide variety of indirect-fire weapons has been modeled under laboratory conditions by using fragment simulating projectiles. The study was conducted in order to gain information on the relative effectiveness of various field-available materials for use as protection from fragments. In addition to establishing the relative effectiveness of various textiles, wood, sand, and clay, an insight into the mechanics of fragment penetration in these materials was also gained. This additional information was useful in material selection, location, orientation, etc., for maximum effectiveness as fragment protection. Other basic engineering details such as the effects of moisture, air gaps, obliquity, etc., which could alter the effectiveness of a protection scheme were also researched and discussed.

Research should be continued on items of military interest, and any new material that is developed can be immediately evaluated for possible military application. In the future, some attention should be given to the problem of constructing a table or other set of data that will give comparative effectiveness of a wide range of materials. Such a collection should include data on ballistic nylon, plywood, various landing mats, earth materials, etc.

TABLE 1 CRITICAL VELOCITY, ELONGATION, AND ENERGY FOR VARIOUS PROTECTIVE MATERIALS

Material	Transverse Critical Velocity	Breaking Elongation	Specific Breaking Energy
	ft/sec	percent	joules/gram
Acetate	1,115	30.7	34.9
Glass fiber	1,420	2.6	8.1
Nylon	2,240	11.1	38.5
Polyester	1,830	8.0	24.3
Rayon	1,465	13.1	25.8

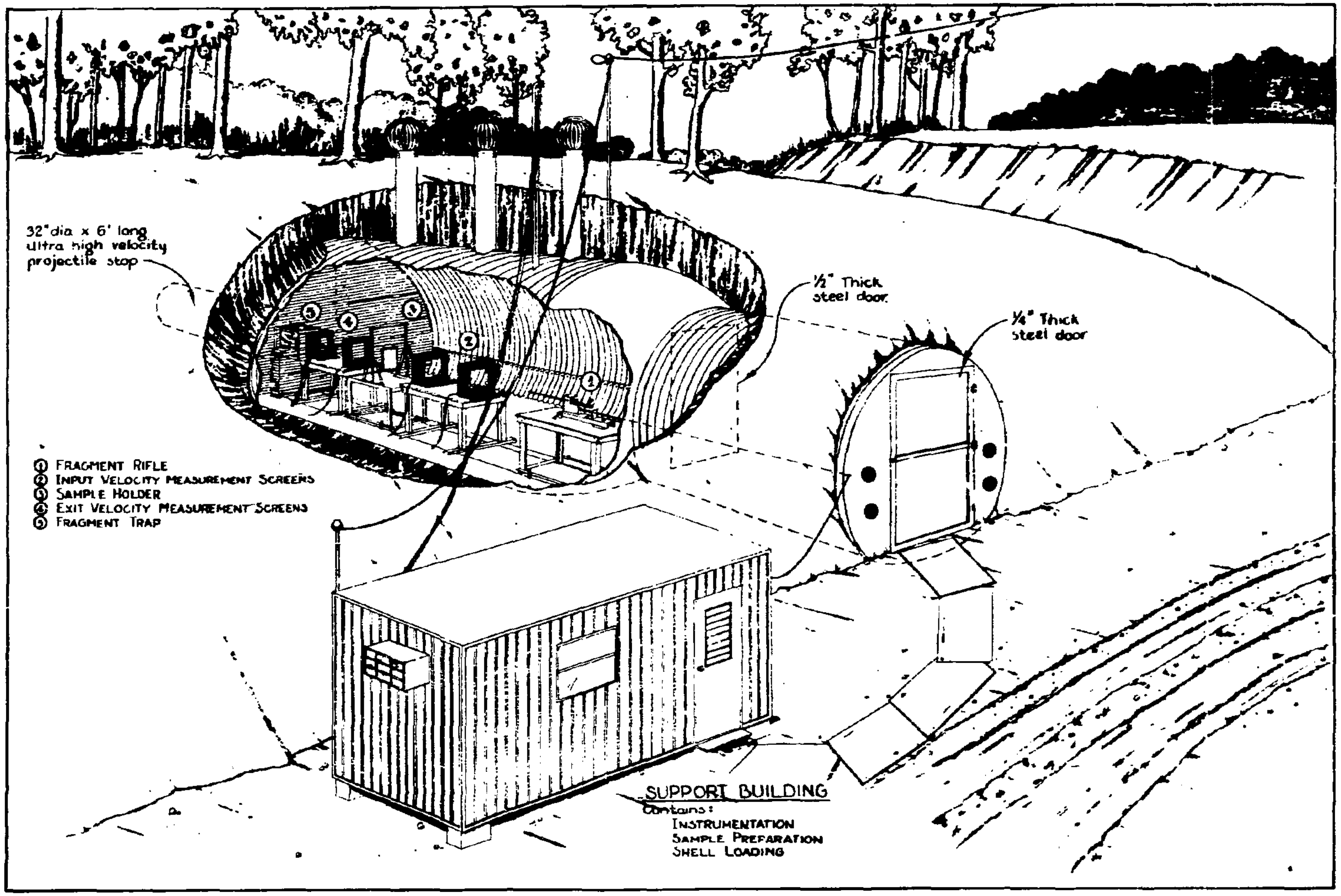


Figure 1 Fragment simulation facility.

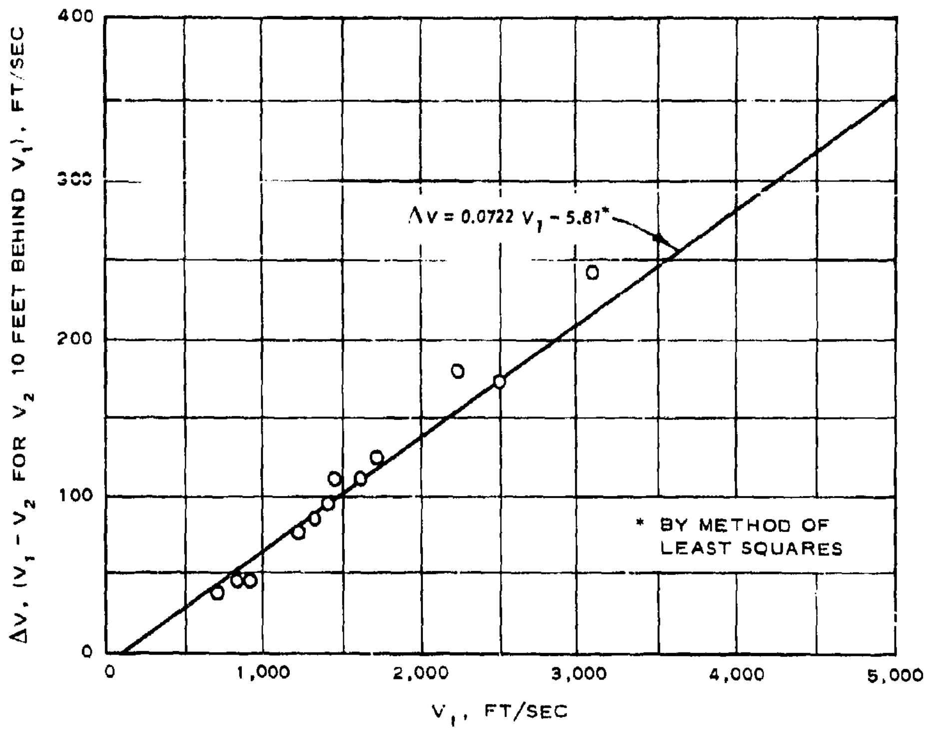


Figure 2 Velocity loss for 21-grain cube passing through 10 ft of air.

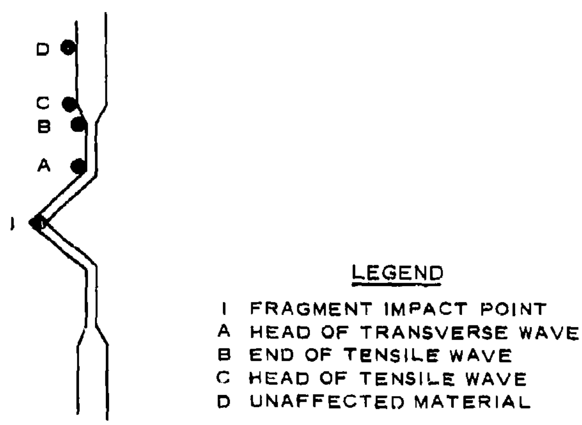


Figure 3 Impacted filament prior to breaking.

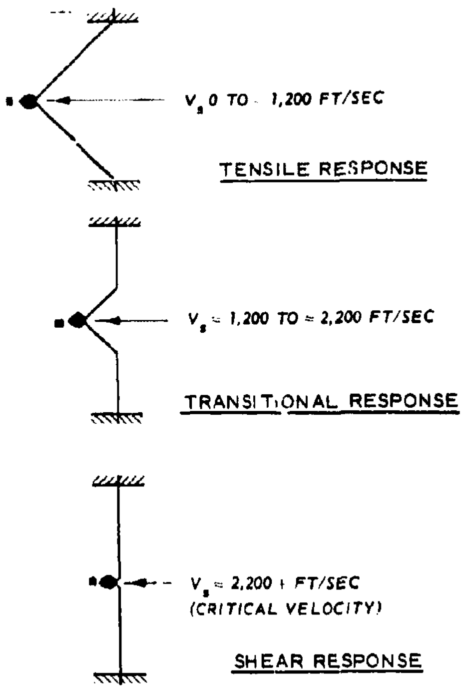


Figure 4 Failure patterns for nylon filament (V_s is striking velocity).

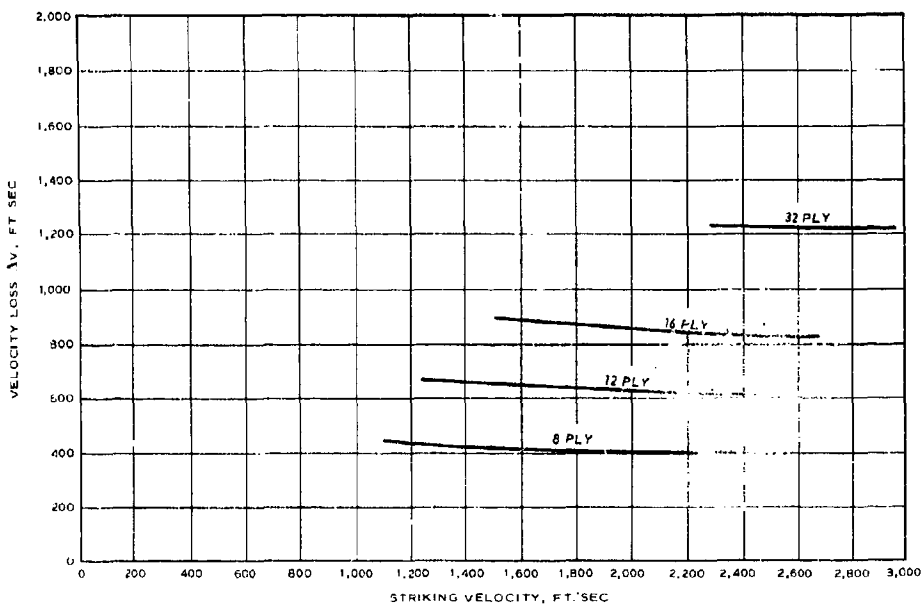


Figure 5 Velocity loss for 21-grain cube in complete penetration of nylon.

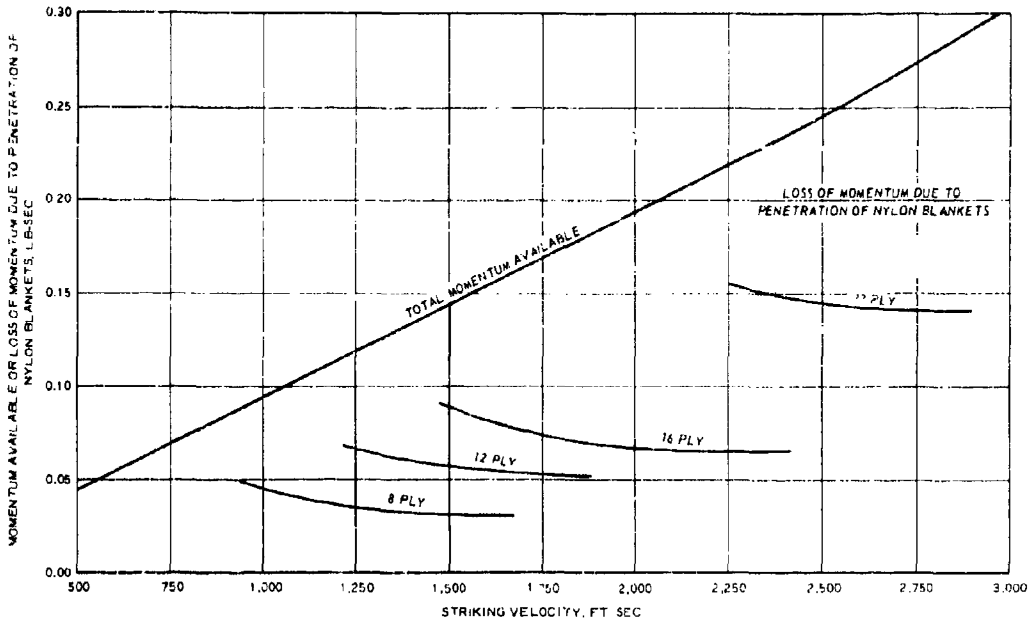


Figure 6 Change in momentum for 21-grain cube penetrating ballistic nylon.

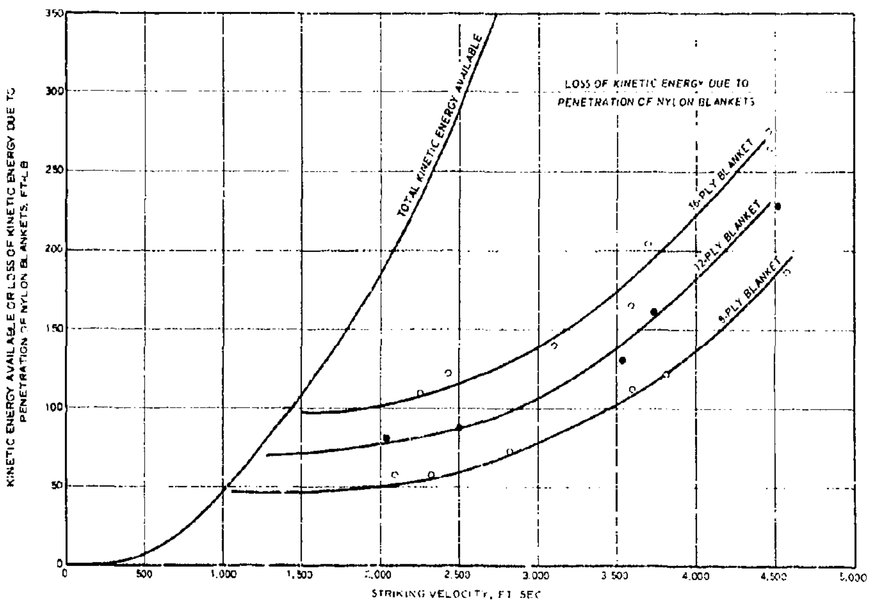


Figure 7 Energy loss for 21-grain cube in penetration of 8-, 12-, and 16-ply nylon blankets.

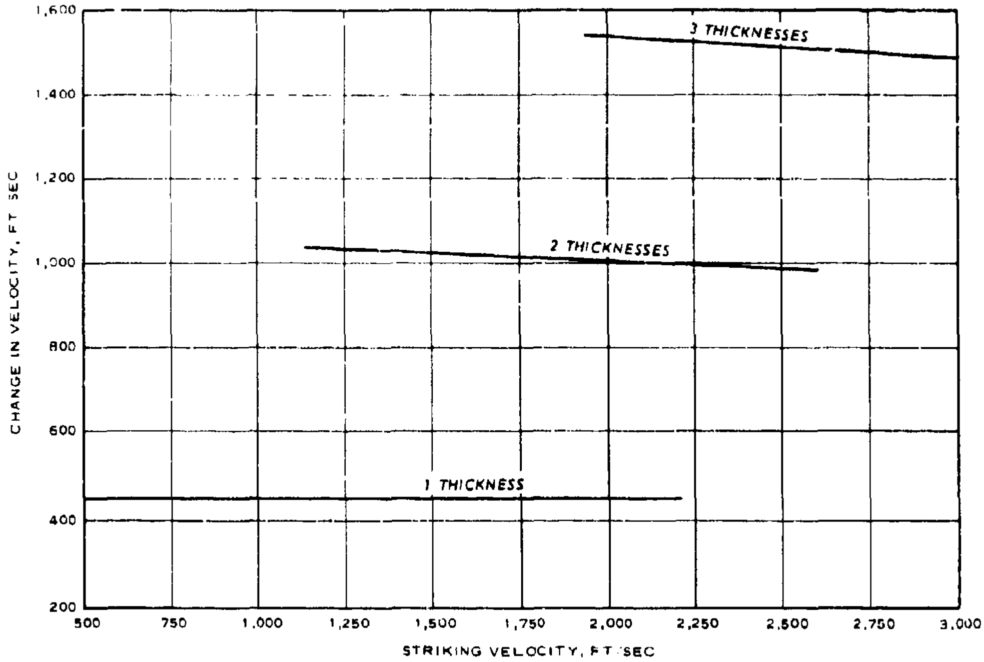


Figure 8 Velocity loss for 21-grain cube in 3/4-inch plywood.

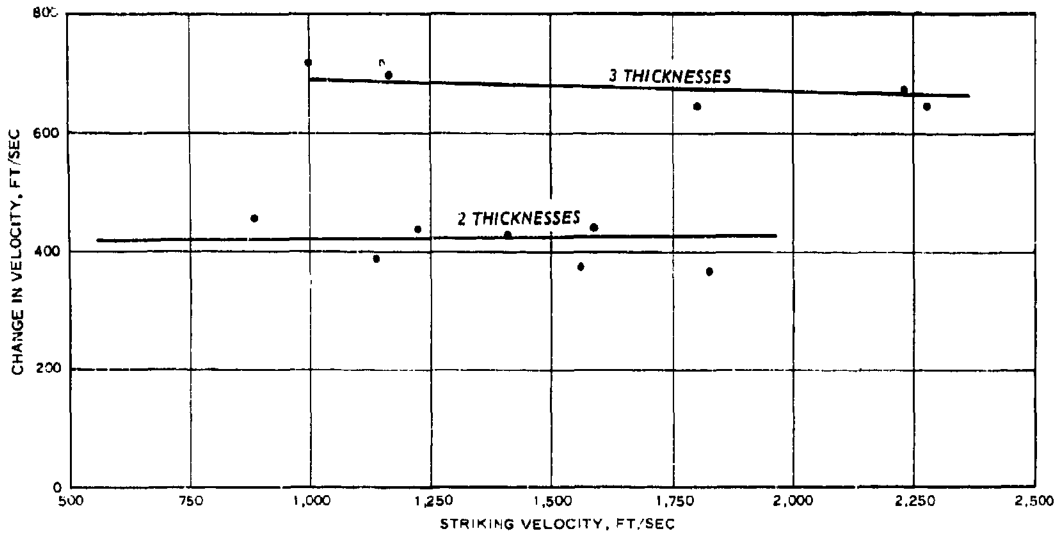


Figure 9 Velocity loss for 303-grain cylinder passing through 2 and 3 thicknesses of 3/4-inch fir plywood.

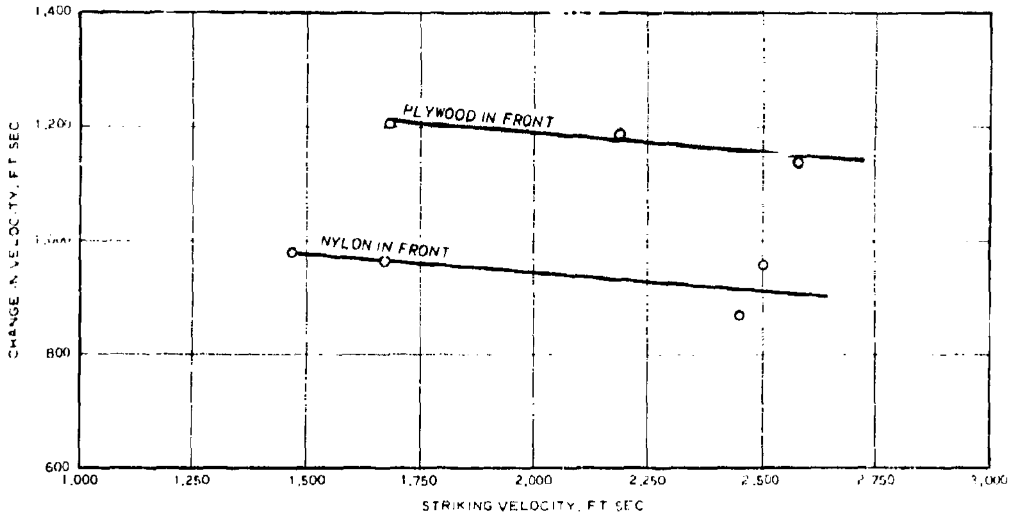


Figure 10 Velocity loss for 21-grain cube passing through combinations of 8-ply nylon and 3/4-inch fir plywood.

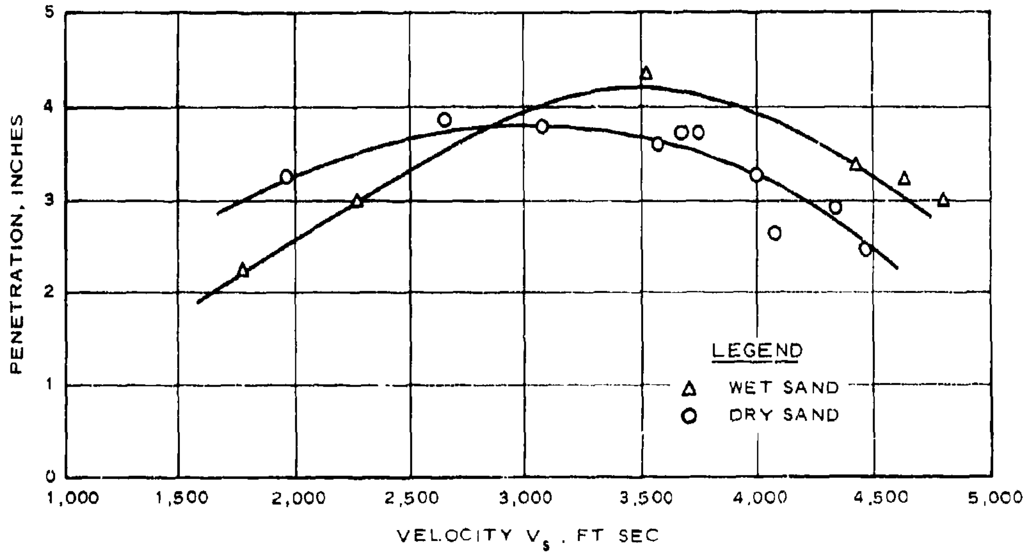
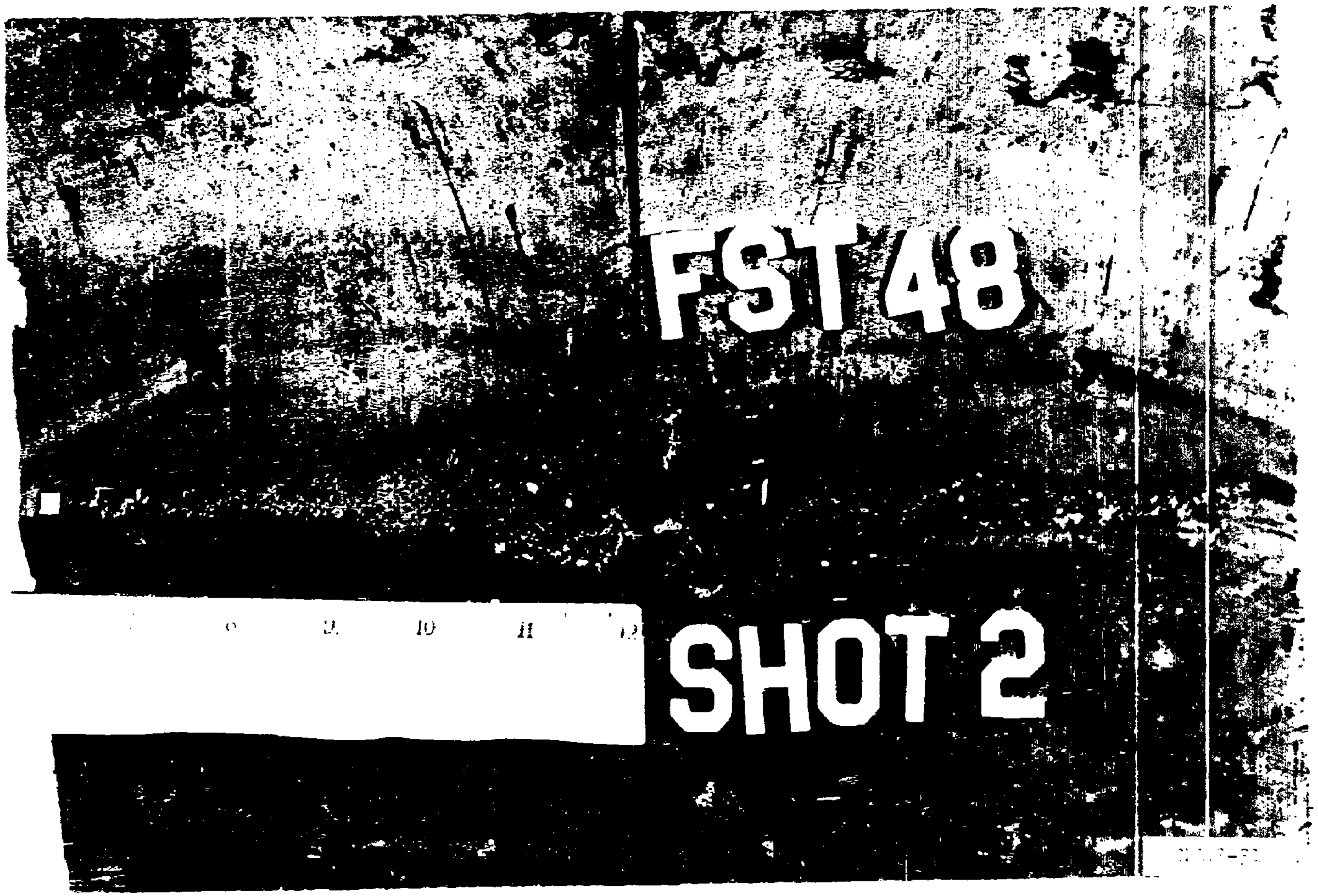


Figure 11 Penetration in sand of 21-grain steel cube fragment simulating projectile.

Figure 12 Cavity in clay resulting from impact of Shot 1 projectile (V_s = 1,840 ft/sec).



a. LEFT HALF

b. RIGHT HALF

Figure 13 Sectioned cavity in clay resulting from impact of Shot 2 projectile (V_s = 2,375 ft/sec).

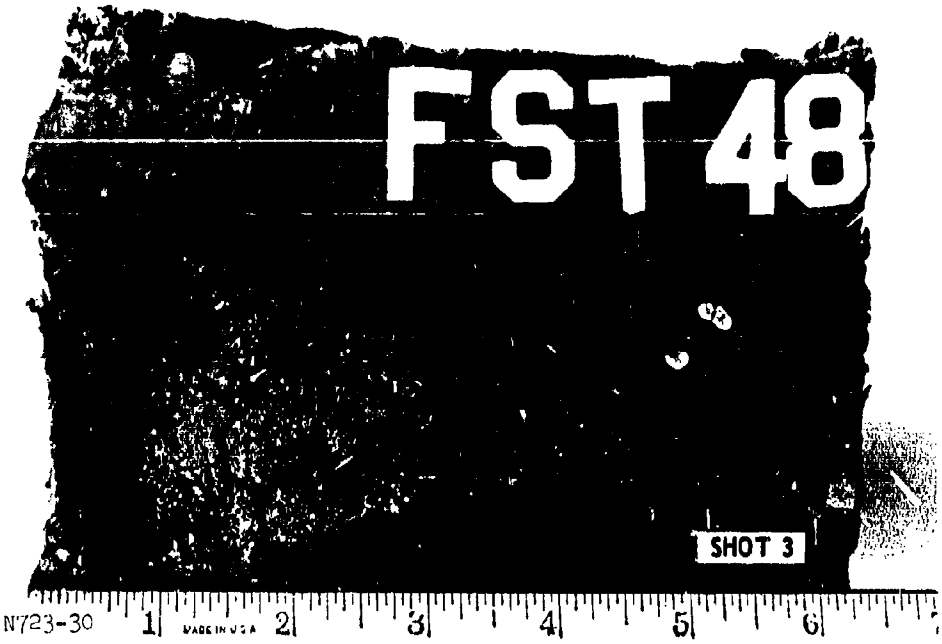


Figure 14 Cavity in clay resulting from impact of Shot 3 projectile (V_s = 2,990 ft/sec).

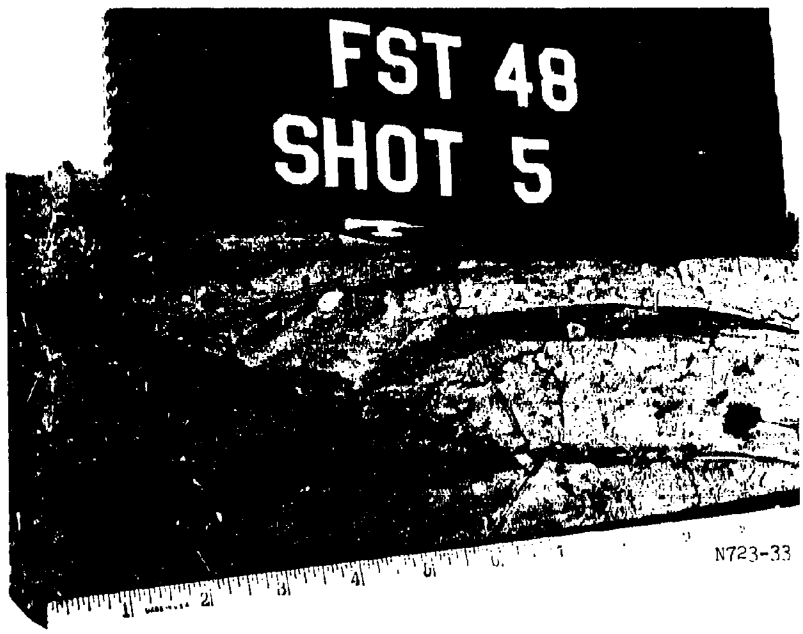


Figure 15 Cavity in clay resulting from impact of Shot 5 projectile (V_s = 3,930 ft/sec).

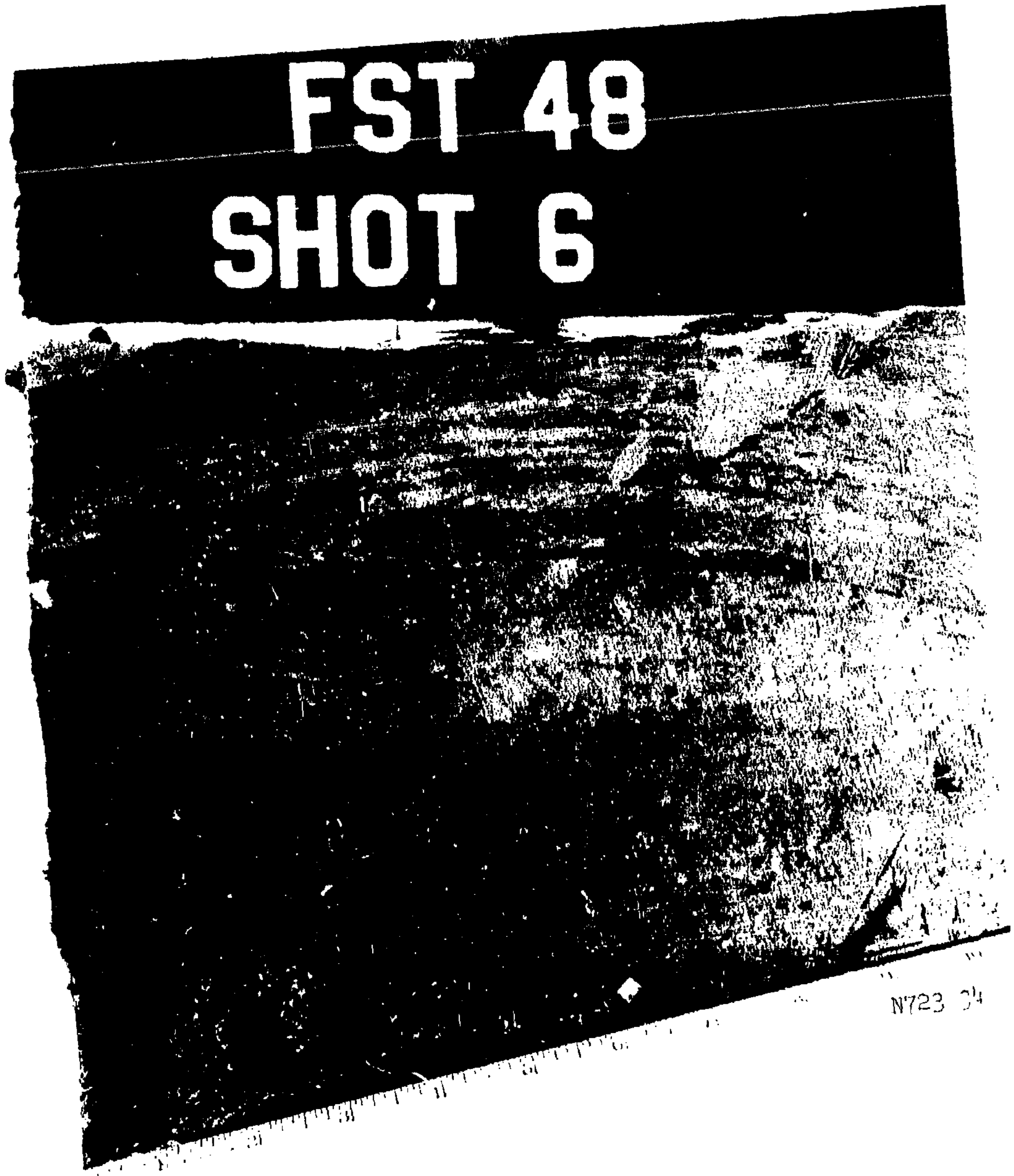


Figure 16 Cavity in clay resulting from impact of Shot 6 projectile (V_s = 4,320 ft/sec).